Gestures for Smart Rings: Empirical Results, Insights, and Design Implications

Bogdan-Florin Gheran
MintViz Lab | MANSiD
Research Center,
University of Suceava
Suceava 720229, Romania
vatavu@eed.usv.ro

Jean Vanderdonckt
Louvain School of
Management, Univ.
catholique de Louvain
Louvain-la-Neuve, Belgium
jean.vanderdonckt@uclouvain.be

Radu-Daniel Vatavu
MintViz Lab | MANSiD
Research Center,
University of Suceava
Suceava 720229, Romania
vatavu@eed.usv.ro

ABSTRACT
We present empirical results about users' gesture preferences for smart rings by analyzing 672 gestures from 24 participants. We report an overall low consensus (mean .112, maximum .225 on the unit scale) between participants' gesture proposals, and we point to the challenges of designing highly-generalizable ring gestures across users. We also contribute to the practice of gesture elicitation studies by discussing how *a priori* conditions (e.g., participants' traits, such as creativity and motor skills), commitment and behavior *during* the experiment (e.g., their thinking times), but also *a posteriori* aspects (the experimenter's choice of criteria to group gestures into categories) affect agreement. We offer design guidelines for ring gestures informed by our empirical observations, and present a collection of gestures reflective of our participants' mental models for effecting commands using smart rings.

ACM Classification Keywords
H.5.2. [Information Interfaces and Presentation (e.g., HCI)] User Interfaces: *Input devices and strategies*.

Author Keywords
Smart Rings; Ring Gestures; Gesture User Interfaces; Elicitation Study; Wearables; Experiment; Design Guidelines.

INTRODUCTION
In J.R.R. Tolkien's "The Lord of the Rings" [48], extraordinary events take place as a direct consequence of the magical powers of one ring. Common in fiction, magical rings enable their owners to perform outstanding acts and gain superhuman powers, such as to control objects with a mere twist of a finger; see the "Rings" entry in Clute and Grant's "Encyclopedia of Fantasy" for an overview of magical rings imagined by the creative authors of the fantasy literature [8]. For centuries, humans could only dream of such fantastic experiences. However, recent advances in miniaturization, communications, and the richness of high-fidelity sensors have paved the way to a world in which wearables can implement spectacular visions of mobile computing [31,60]. In fact, we have reached a turning point in miniaturization where active rings, known as "smart rings," are no longer fantasy. Smart rings can be rigorously prototyped to mediate interactions with the physical objects and space around us [17,27,35,61,67,68].

Figure 1. Smart rings afford a variety of touch and mid-air gesture input. In this work, we employ Ring Zero devices [28], as illustrated in this picture, to elicit and understand users' preferences for ring gestures.

To this end, smart rings embed a variety of electronics, such as micro-controllers, inertial measurement units, LEDs, and Bluetooth modules, and can be programmed to react to events produced by their owners or sensed directly from the context of use [36,37]. For instance, the Ring Zero device (Figure 1) enables its owners to play music on a connected smart device by recognizing gestures in mid-air [28]. Although ring technology is still in its infancy, several startups and projects are under progress at the moment of this writing, generating impressive interest on crowdfunding campaigns, such as OURA [37], ORII [36], or Nimb [34], to name just a few.

While smart ring technology is developed, the majority of effort has been put into miniaturization and industrial design [17,27,35] and algorithms to recognize ring gestures effectively [61,67,68]. However, no investigation has been conducted on *users' preferences for ring gestures* and, consequently, there is little information available to (i) *designers and practitioners* about what types of gestures to utilize in their prototypes, (ii) *manufacturers* regarding desirable features to include in the future versions of their smart rings, or (iii) to *researchers* to employ relevant criteria to analyze users'

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ring gestures. This work represents the first investigation to inform gesture UI design for smart rings by providing insights and implications for design resulted from an elicitation study.

The contributions of this work are two-fold:

1. We conduct the first scientific investigation to collect, analyze, and understand users' preferences for ring gestures. Our practical results consist in:
   (a) An analysis of agreement between participants' gestures for contexts of use with one and two smart rings.
   (b) A generic taxonomy for ring gestures with 5 dimensions (nature, structure, complexity, symmetry, and locale) to analyze and inform ring gesture designs.
   (c) A collection of representative gestures reflective of our participants' conceptual models for effecting commands using smart rings.
   (d) A discussion and a set of practical recommendations for designing ring gesture commands.

   We believe that these practical results will be useful to designers that wish to prototype ring gesture user interfaces tailored to and informed by actual user behavior.
2. Besides our practical findings in terms of what ring gestures are preferable, we also contribute to the generic gesture elicitation methodology [57,62,63] with insights on how various factors, related to either the participants or the experimenter, can affect the level of consensus for *any* elicitation study. To this end, we use our specific investigation on ring gestures to point the community to important aspects to consolidate the practice of conducting gesture elicitation studies.

RELATED WORK

We overview in this section prior work on smart rings with a focus on gesture input techniques. We also discuss the elicitation methodology [57,58,63] that we employ in this work to collect and analyze users' preferences for ring gestures.

Smart Ring Prototypes and Technology

The first ring device known in history, dating from the Chinese Qing Dynasty, inlaid a tiny abacus with 1 mm-wide beads operated using a pin [7]. The first electronic prototype (1997) was Fukumoto and Tonomura's "FingerRing" [12] that embedded an accelerometer to detect gesture input in the form of taps performed with the fingertips. Since then, electronic rings have elicited researchers and practitioners' imagination and creativity, and many designs emerged with various input and output capabilities [4,24,27,66,67]. Current smart ring designs typically fall into one of two categories [4,41]: *output-only* devices that notify their owners about the occurrence of predefined events (e.g., incoming messages or alerts) and *input-and-output* rings that listen to user input and effect commands (e.g., to control other devices). In this work, we are interested in smart rings of the latter kind.

Various technologies have been used to prototype ring devices. For instance, Ogata et al.'s "iRing" [35] utilized infrared reflection to detect directional gesture swipes and finger bending; "Magic Ring" [17] used an accelerometer to detect motion gestures; the rotations and sliding of "Nenya" [4] were detected via magnetic tracking; "OctaRing" [27] implemented pressure-sensing multi-touch input; the "eRing"prototype of Wilhelm et al. [61] employed electric field sensing to detect multiple finger gestures; and "LightRing" [20] used infrared proximity sensing and a gyroscope to locate the fingertip on any surface for cursor pointing and target selection.

Recognition of gestures performed with smart rings has been implemented with rule-based systems that use the orientation of the ring [17], detection of the ring's rotation and sliding directions [4], calculations on quaternions [28], nearest-neighbor classification and the dynamic time warping function to match ring gestures with templates [67], or more complex approaches, such as Support Vector Machines [67], decision trees, and neural networks [42]. As long as ring gestures can be described as time-ordered series of points in 2D or 3D [51], any state-of-the-art stroke-gesture recognition algorithm, including the recognizers of the "$-family," such as $1, $N, $P, $P+, Protractor, or $3 [3,22,25,53,55,64], to name just a few, could be employed to classify ring gestures effectively.

Interactive Techniques for Smart Rings

Smart rings afford a wide range of touch, motion, and mid-air gesture interactions. However, despite the rich literature on generic gesture input [38,43,59,63], prior work on smart rings has employed small gesture sets of simple gesture types [11,17,66]. For instance, the "Magic Ring" prototype of Jing et al. [17] employed four gestures only: pointing the finger up/down and left/right to control home appliances, such as a lamp, radio, and a TV set. "RingIoT" [11], a smart ring for controlling devices in an Internet-of-Things (IoT) ecosystem, implemented pointing, directional movements, and simple shapes, such as a "circle" drawn in mid-air. A similar vocabulary was used by Zhang et al. [66], who designed a technique to turn any uninstrumented surface into an interactive one with six gestures: four directional swipes, a "click," and the "circle" shape. Overall, for most ring gestures proposed in prior work, a very limited vocabulary of gesture types was involved.

Exceptions to this trend are creative gesture designs specific to some smart rings only, such as "i-Throw", "Nenya", "OctaRing", and "Frictio" [4,15,24,27]. The "i-Throw" ring [24] incorporated "throwing", "receiving", and "scanning" gestures for a location-based service environment. "Nenya" [4] implemented item selection from menus by twists of the ring and "clicks" by sliding the ring along the finger. Other creative gestures emerged from specific ring form factors [9]. For instance, "OctaRing" [27], with its octagonal shape, was designed to detect multi-finger pressure input on its sides; "Frictio" delivers passive kinesthetic force feedback on rotational input [15]; and "Ringteraction" [13] exploits unique biomechanical characteristics of the human hand to support micro-interactions.

Gesture Elicitation Studies

Understanding users' preferences and behavior with new interactive technology right from the early stages of design empowers designers with valuable information to shape a product's characteristics for more effective and efficient use. This process is known as "participatory design" [5,19], and its specific implementation in the gesture literature in the form of "guessability studies" [62] or "gesture elicitation studies" [57,58,63] has been extremely popular to understand users' preferences

Figure 2. Snapshots from the elicitation study showing participants performing gestures using one or two smart rings (highlighted in each image).

for gesture input for a variety of application domains and devices [38,43,50,59,63]. For instance, Wobbrock et al. [63] reported users' preferences for multi-touch input on interactive tabletops; Vatavu [50,52] and Zaiţi et al. [59,65] addressed mid-air gesture input to control the TV set; Ruiz et al. [43] investigated users' preferences for motion gestures performed using smartphones; Lou et al. [30] looked at motion gestures for cyber-physical smart home environments; and Piumsomboon et al. [38] examined gesture commands for augmented reality applications, to name just a few examples. The outcome of a gesture elicitation study consists in a characterization of users' gesture input behavior with valuable information for designers and practitioners regarding the consensus levels between participants (computed as *agreement* or *coagreement rates* [57,58,63]), the most frequent (thus, generalizable across users) gesture proposals for a given task, and insights into users' conceptual models for performing tasks. The most recent formalization of the elicitation methodology was proposed by Vatavu and Wobbrock for both repeated measures [57] and between-subjects [58] experimental designs.

Summary

Ring-based gesture input has a lot of potential for a variety of contexts of use [46], from control applications, gaming, and autonomous vehicles [12,13,17] to smart spaces [11,20,24,42,49] and collaborative environments [14]. Prior work has focused almost exclusively on prototyping ring technology and neglected systematic exploration of how ring gestures can be effectively designed and mapped to commands. Thus, the community lacks relevant knowledge about *how to design intuitive ring gestures reflective of user behavior*. A solid, rigorous understanding of users' gesture preferences will unquestionably benefit all the aforementioned application domains. In this work, we make the first step towards such an understanding.

EXPERIMENT

We conducted a gesture elicitation study following the methodology from the literature [38,43,50,57,62,63] to collect users' preferences for ring-based gesture input. Before we continue, we provide our definition for ring gestures, as follows:

> A "ring gesture" is any action performed *with* or *on* a smart ring or any movement of the wearing finger and/or hand that causes a detectable change in the ring's position and/or orientation in a system of reference centered on the user's finger or body.

By adopting this definition, we follow Shilkrot et al. [46], who compiled a comprehensive survey of finger augmentation devices and made the distinction between *contact-based* and *contactless* input on smart rings. In the first case, gestures are performed on the ring surface and usually mimic interactions common on touchscreens, such as taps, pinch gestures, or directional swipes. But contact-based input on the small surface of a ring can only provide a limited vocabulary of mostly predefined gesture types. Contactless input, however, offers designers a richer design space for mid-air gestures and end-users more opportunities to customize gestures to their own preferences. In this work, we adopt a comprehensive approach, reflected in our definition of ring gestures, by examining both contact-based and mid-air input for smart rings, including combinations thereof. Thus, all the following examples are valid ring gestures for the purpose of this study:

> *Example*: Touch the ring once, twice, or multiple times in a row. Tap a rhythmic pattern on the ring's surface.

> *Example*: Rotate the ring on the finger. Rotate the finger wearing the ring. Rotate the hand wearing the ring.

> *Example*: Slide the ring along the finger. Pull out the ring. Place the ring back on the finger. Change the ring to a different finger, etc.

> *Example*: Draw a gesture in mid-air, such as a "question mark" symbol, with the finger wearing the ring. Place the finger or the hand wearing the ring in a specific position with respect to the body, e.g., near the mouth.

> Any combination of the above.

Participants

Twenty-four (24) participants (9 female), aged between 21 and 45 years old ($M = 27.5$, $SD = 7.9$ years), volunteered for our study. Participant occupations included students (Computer Science), psychologist, teacher, lawyer, police officer, interpreter, office clerk. Of all participants, 79% (19/24) had a technical background. We chose the age group of our participants to be as representative as possible for adopters of wearable technology.[1] The majority of participants ($22/24 = 91.7\%$) were right-handed. All participants owned smartphones and, thus, were accustomed with touch and gesture input.

[1] Statistics show that the percentage of individuals who use wearables is the highest for the age group 25–34 years old (30.8%), followed by the 18–25 years old age group (29.1%), and the 35–44 years old group (25.3%), according to http://www.emarketer.com/Chart/US-Wearable-User-Penetration-by-Age-2017-of-population-each-group/202360.

Apparatus
We employed two Ring Zero devices [28] (see Figure 1), which participants wore on their index fingers of each hand; see Figure 2 for a few snapshots captured during the study. Ring Zero reports changes in its orientation to a Bluetooth 4.0 connected device, such as a smartphone. The ring also features a touch button that detects short (< 2 s) and long presses (> 2 s).

Task
Participants were presented with the two rings and were given time to familiarize with the new technology (none of them had used smart rings before this study). The experiment consisted of two sessions, during which participants wore one ring and both rings, respectively. Each session implemented the gesture elicitation protocol [63]: participants were presented with *referents*, i.e., functions to control in a home environment, described next in this section, for which they proposed suitable gestures to execute those referents, i.e., gestures that fit referents well, are easy to produce and remember. We did not constrain participants' choices of gestures to any particular context of use (e.g., on the ring) or to any hardware ability (e.g., motion gestures only), as such an influence would have inconveniently narrowed the findings of this first exploratory study on ring gestures. The experimenter clarified all participants' questions before the study, e.g., regarding the type of gestures (all types were allowed) or the possibility to assign a given gesture to more than one referent (not allowed). Participants operated with the belief that any gesture they performed was recognizable.[2] The order of the referents was randomized per participant. Participants' fine motor skills and creativity levels were evaluated before the experiment, and a short questionnaire was administered after the experiment.

Design
Our study was within-subjects with two independent variables:

1. REFERENT, nominal variable with 14 conditions, representing common tasks to execute in a home environment with a smart ring: (1) turn the TV on/off, (2) start player, (3) turn the volume up and (4) down, (5) go to the next and (6) previous item in a list, (7) turn AC on/off, (8) turn lights on/off, (9) brighten and (10) dim lights, (11) turn heat on/off, (12) turn alarm on/off, (13) answer and (14) end phone call.
2. NUMBER-OF-RINGS, ordinal variable with two conditions, corresponding to two contexts of use: 1-ring and 2-rings.

Our choice of referents was inspired from other elicitation studies [23,50,59] that examined generic tasks for smart homes. Also, most of the tasks are mutually exclusive (e.g., turn on/off the TV) and, according to the context, they can be executed with the same gesture command, e.g., if the TV is on, performing the gesture will turn it off and vice versa We adopted this design approach to reduce the number of gesture commands that users would need to learn and recall. Moreover, previous studies reported users' preferences for employing the same gesture type to perform "on/off" tasks, such as turn on/off devices or pop up/hide menus [50,59].

[2]This approach enabled participants to invent gestures beyond the hardware abilities of the rings, which represents a useful result that can potentially inform new technology design for smart rings.

Measures
We employed the following measures to evaluate and understand users' preferences and cognitive and motor performance for gestures produced with or on smart rings:

1. We computed agreement rates (AR) for each REFERENT and NUMBER-OF-RINGS conditions using the formula of Vatavu and Wobbrock [57] (p. 1327), as follows:
$$AR(r) = \frac{\sum_{i<j} \delta_{i,j}}{n \cdot (n-1)/2} \quad (1)$$
where n is the number of participants from which gestures are elicited, and $\delta_{i,j}$ evaluates to 1 if the i-th and j-th participants are in agreement over referent r and to 0 otherwise.
2. Participants' creativity was evaluated before the elicitation procedure using a generic creativity test. The test is available on-line[3] and reports a score between 0 and 100 (higher scores denote more creativity) computed from answers to a set of 40 questions. We specifically chose this test due to its ease of application and large diversity of factors evaluated: *abstraction* (of concepts from ideas), *connection* (between things without an apparent link), *perspective* (shift in terms of space, time, and other people), *curiosity* (to change and improve things accepted as the norm), *boldness* (to push boundaries beyond accepted conventions), *paradox* (the ability to accept and work with contradictory concepts), *complexity* (the ability to operate with a large quantity of information), and *persistence* (to derive stronger solutions even when good ones have already been generated).
3. We measured participants' fine motor skills with a standard motor test of the NEPSY test batteries (a developmental NEuroPSYchological assessment) [21]. The test consists in touching each fingertip with the thumb of the same hand for eight times in a row. Higher motor skills are reflected in less time to perform this task.
4. THINKING-TIME measures the time, in seconds, needed by participants to propose a gesture for a given referent.
5. GOODNESS-OF-FIT represents participants' subjective assessment, as a rating between 1 and 10, of their confidence about how well the proposed gestures fit the referents.

RESULTS
We collected a total number of 672 gesture proposals from 24 (participants) $\times$ 14 (referents) $\times$ 2 (number of rings) conditions, which we clustered into groups of similar gesture types according to the following criteria:

1. *Handedness*. Gestures performed with the dominant hand are considered different from those performed with the nondominant hand, e.g., "circles" drawn with the dominant/nondominant hand fall into distinct categories.
2. *Scale*. Gestures performed at different scales go into distinct categories, e.g., a large amplitude "circle" performed with the entire arm is considered different from a small "circle" performed with the finger. For the purpose of this study, we considered three scales (large, medium, and small) corresponding to arm, wrist, and fingers' ranges of movements.

[3]http://www.testmycreativity.com/

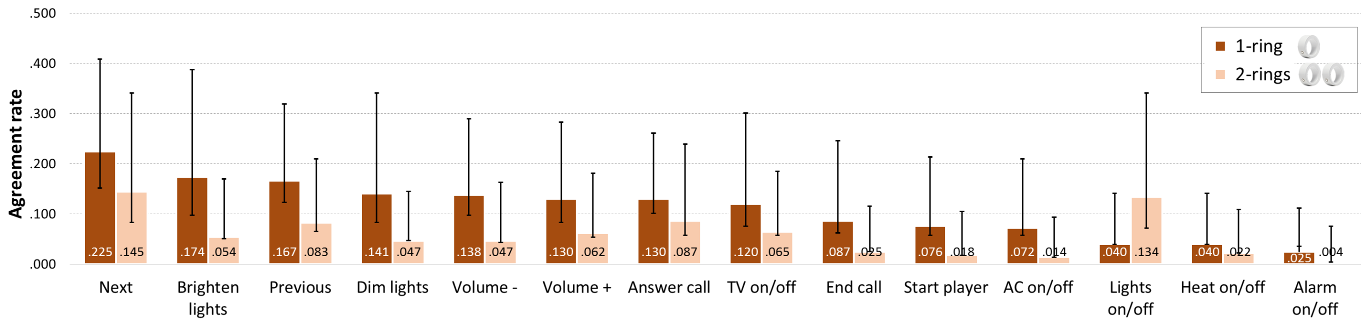

Figure 3. Agreement rates for gesture proposals elicited with one and two rings, respectively. Notes: referents are ordered on the horizontal axis in descending order of their agreement rates for the 1-ring condition; error bars show 95% CIs computed with the AGATe tool [57].

3. *Direction*. The same gestures performed in different directions are considered different, e.g., clockwise and counterclockwise "circle" shapes drawn in mid-air.
4. *Hand pose*. We considered that specific hand poses adopted by participants during gesture articulation contain relevant information for the gestures' meaning, e.g., a "circle" performed with the open hand is considered different from the same "circle" drawn with the index finger pointed.
5. *Ring use*. We differentiated between various actions performed *on* the rings. For instance, short presses (less than 2 s) on the touch button located on the smart ring were considered different from longer presses. Also, touching the ring with the thumb of the wearing hand is a different gesture than using the index finger of the other hand.

We identified 81 distinct gestures for the 1-ring condition and 139 gestures (+72% more) for the 2-rings condition. Next, we analyze the consensus between participants' gesture proposals, and assign gesture types to meaningful categories.

Consensus between Proposed Gestures

Figure 3 shows the agreement rates obtained for each REFERENT and NUMBER-OF-RINGS conditions. Overall, agreement rates are very small in magnitude, between .025 and .225 for 1-ring gestures (M=.112, SD=.058) and between .004 and .145 for the 2-rings condition (M=.058, SD=.043). These results are very close to the lowest ever reported agreement rates in the literature of gesture elicitation; see Vatavu and Wobbrock [57] (p. 1332) that summarize agreement rates of 18 studies, for which the smallest value (.108) was reached by Liang et al. [26] and Seyed et al. [45] for motion+surface and multi-display gestures, respectively. According to the recommendations of Vatavu and Wobbrock [57] to interpret the magnitudes of agreement rates, our results fall inside or are close to the low consensus ($\leq .100$) category. These results were confirmed by Kendall's coefficient of concordance:[4] $W = .108$ for 1-ring gestures ($\chi^2(13) = 33.552$, $p < .001$) and $W = .110$ for 2-rings ($\chi^2(13) = 34.389$, $p < .001$). As Kendall's coefficient is related to the average of Spearman correlation coefficients between pairs of rankings [18] (p. 276), we can interpret the magnitude of its effect as small (close to .100) according to Cohen's suggested limits for interpreting effect sizes.

Although consensus was low overall, we nevertheless found that gestures performed in the 1-ring condition led to 93% more agreement than 2-rings gestures. A paired t-test revealed a statistically significant effect of NUMBER-OF-RINGS on AGREEMENT-RATE ($t_{(13)}$=3.985, p=.002, $r = .741$). We also found that the rankings of referents correlated significantly for the two conditions (Spearman's $\rho_{(N=14)}$=.556, p=.039<.05).

It is interesting at this point to look at a shortlist of gesture proposals; see Table 1. Even this shortlist of most frequent proposals includes a wide range of gesture types, ranging from touch input (such as "touch the ring once" or "touch both rings simultaneously") to hand poses (e.g., the "call me" sign performed by placing the thumb near the ear and the little finger pointed at the mouth), and to motion gestures performed in mid-air (flicks to increase or decrease volume). Inspired by the diversity of these first results, we decided to run a thorough classification of all gestures into meaningful categories.

Taxonomy of Ring Gestures

To better understand our participants' ring gesture proposals, we considered the following five dimensions of analysis, inspired by previous gesture studies [38,43,63] and informed by the specifics of ring gestures:

1. *Nature* describes the meaning of a gesture, with three categories: (a) *symbolic*, (b) *metaphorical*, and (c) *abstract*. Symbolic gestures depict commonly accepted symbols employed to convey information, such as emblems and cultural gestures, e.g., the "call me" gesture performed with the thumb and little finger stretched out to denote a phone call, or swiping the index finger from left to right, a convention on touchscreens to access the previous item in a sequence. Metaphorical gestures give shape to an idea or concept, such as using the thumb to press a button on an imaginary remote control to turn on/off the TV set or turning an invisible knob in mid-air. Abstract gestures have no symbolic or metaphorical connections to their referents, and the mapping is arbitrary, e.g., touch the ring twice to answer a phone call. We adapted the nature dimension from Wobbrock et al. [63], who used it for multi-touch gestures.

2. *Structure* characterizes the relative importance of hand poses versus hand motion in the articulation of a ring gesture, with five categories: (a) *buttons-only*, (b) *hand poses only*, (c) *hand motion*, (d) *hand poses & motion*, and (e) *mixed locales*. For instance, for the buttons-only category,

[4] Kendall's W is a normalization of the Friedman statistic used to assess the agreement between multiple raters with a number ranging between 0 (no agreement at all) and 1 (perfect agreement).

Referent	1-Ring			2-Rings[§]		
	AR	Most frequent	Second most frequent	AR	Most frequent	Second most frequent
1. *TV on/off*	**.120**	Press button on an imaginary remote control	Touch the ring once	**.065**	Press button on an imaginary remote control	Touch both rings simultaneously
2. *Start player*	.076	Press imaginary button in mid-air	Press button on an imaginary remote control	.018	Press imaginary button in mid-air	Flick to the right
3. *Volume up*	**.130**	Circle clockwise	Flick upwards	**.062**	Circle clockwise	Flick upwards
4. *Volume down*	**.138**	Flick downwards	Circle counter-clockwise	.047	Flick downwards using both hands	Circle counter-clockwise
5. *Next*	**.225**	Flick to the right	Flick to the left	**.145**	Flick to the right	Flick to the right using both hands
6. *Previous*	**.167**	Flick to the left	Swipe on the ring upwards	**.083**	Flick to the left using both hands	Flick to the left
7. *AC on/off*	.072	Raise hand and touch the ring	Touch the ring once	.014	Bring both hands in front and towards the body	Use the hands as a hands fan
8. *Lights on/off*	.040	Raise hand and touch the ring	Clap once	**.134**	Clap once	Raise hand and touch the ring
9. *Brighten lights*	**.174**	Flick upwards	Circle clockwise	.054	Spread palms horizontally	Flick upwards
10. *Dim lights*	**.141**	Flick downwards	Circle counter-clockwise	.047	Flick downwards using both hands	Flick downwards
11. *Heat on/off*	.040	Touch the ring once	Press imaginary button in mid-air	.022	Rub hands	Spread palms horizontally
12. *Alarm on/off*	.025	Touch the ring once	Draw letter "S" in mid-air[‡]	.004	Touch both rings simultaneously	Press several imaginary buttons in mid-air
13. *Answer call*	**.130**	Flick to the right	"Call me" sign[†]	**.087**	Flick to the right	"Call me" sign[†]
14. *End call*	.087	Flick to the left	Touch the ring once and flick to the left	.025	Flick to the left	Flick to the left using both hands

[†]Thumb placed near the ear, little finger pointed at the mouth; [‡]Letter "S" stands for "Security"; [§]Unless indicated explicitly, gestures listed in this column are performed using the ring worn on the dominant hand; Referents with agreement rates above average are highlighted for each condition.

Table 1. First and second most frequent gesture proposals for each referent using one and two rings, respectively. Note how even this shortlist of proposals spans a wide range of gesture types, from touch input to hand poses and motion gestures performed in mid-air.

the gesture employed to press the button is not important: all that matters is that the button was pressed and for how long it was pressed. The hand poses category includes gestures for which the specific configuration of the hand is meaningful, while the movement of the hand is not important (e.g., the "thumbs up" gesture), and so on. This category was inspired by the taxonomy of Vatavu and Pentiuc [56].[5]

3. *Complexity* characterizes a gesture as either (a) *simple* or (b) *compound*. We define simple gestures as gestures that have meaning on their own, e.g., drawing a "circle" in mid-air. Compound gestures can be decomposed into individually meaningful gestures, e.g., pressing a button followed by drawing a "circle." We adopted the complexity dimension from Ruiz et al. [43], who used it to describe user-defined motion gestures for smartphones.
4. *Symmetry* characterizes how the two hands are employed to produce a 2-rings gesture, with four categories: (a) *dominant unimanual*, (b) *nondominant unimanual*, (c) *symmetric bimanual*, and (d) *asymmetric bimanual*. We adopted this dimension from Piumsomboon et al. [38], who used it to characterize users' mid-air gestures for AR applications.
5. *Locale* specifies the location in space where the gesture is performed: (a) *on the ring*, (b) *on other surface*, (c) *in-the-air*, and (d) *mixed locales*, adapted and extended from [38].

[5]Vatavu and Pentiuc [56] refer to the categories of their taxonomy as "simple static", "static generalized", "simple dynamic", and "dynamic generalized" gestures. Although we adopted a different terminology here referring specifically to hand poses and motion, the categories are practically the same.

Gesture dimension	Pearson's χ^2	p-value	Cramer's V
1. *Nature*	$\chi^2(2) = 5.503$	*n.s.*	.090
2. *Structure*	$\chi^2(4) = 68.556$	$p < .001$	.319
3. *Complexity*	$\chi^2(1) = 4.154$	$p = .051$	.079
4. *Symmetry*	$\chi^2(3) = 307.575$	$p < .001$	.677
5. *Locale*	$\chi^2(3) = 27.030$	$p < .001$	.201

Table 2. The effect of Number-of-Rings on the distribution of participants' gesture proposals for each gesture dimension.

Figure 4 (next page) illustrates the observed percentages of gestures falling in each category. Pearson Chi-Square tests showed significant effects of Number-of-Rings on the distribution of proposed gestures for the *Structure*, *Symmetry*, and *Locale* dimensions ($p < .001$) and a marginally significant effect ($p = .051$) for *Complexity*; see Table 2. Overall, gestures performed with two rings involved more motion than 1-ring gestures (42.3% *vs.* 14.0%) due to the extra degrees of freedom afforded by the second hand. Also, there were more 2-rings gestures on a surface other than the ring than in the 1-ring condition (10.7% *vs.* 2.1%), because the nondominant hand acted as a natural surface to perform gestures on.

Gestures' Goodness of Fit

Participants rated their gesture proposals with numbers from 1 (poor fit) to 10 (excellent fit) to denote their confidence in the goodness of fit of their proposals. A Wilcoxon signed ranks test revealed a statistically significant effect of Number-of-Rings on Goodness-of-Fit

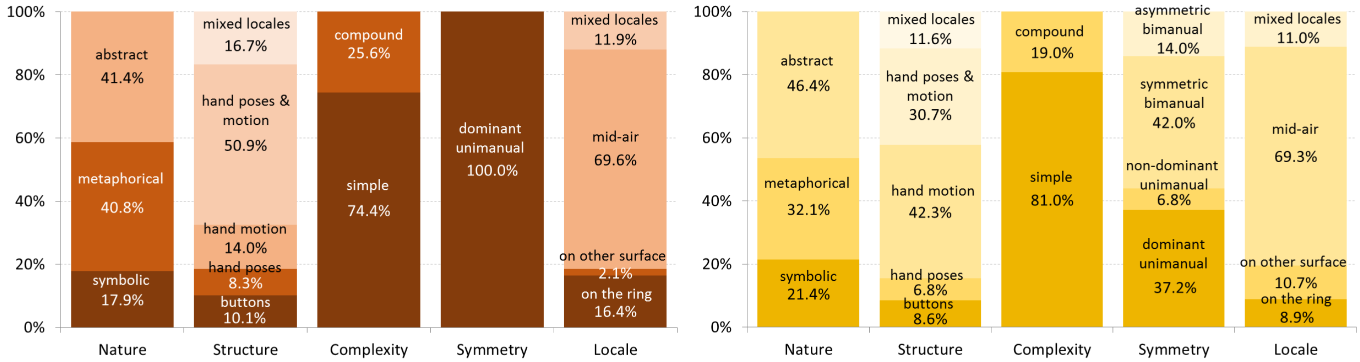

Figure 4. Observed percentages of 1-ring (left) and 2-rings gestures (right) for each category of our taxonomy.

($Z_{(N=14)} = 2.518$, $p = .012$, $r = .476$): participants rated 2-ring gestures (M=8.14, Mdn=8.00, SD=1.26) significantly higher than those produced with one ring (M=7.87, Mdn=8.00, SD=1.41). GOODNESS-OF-FIT correlated significantly with AGREEMENT-RATE for 1-ring gestures (Pearson's $r_{(N=14)}$=.685, R^2=.469, p=.007): referents that reached high agreement rates were assigned gestures that were rated a good fit. This relationship was however not met for the 2-rings condition ($r_{(N=14)}$=.150, p=.609, *n.s.*), probably because of the lower agreement reached overall for 2-rings gestures (.058).

ON THE PROCESS OF REACHING CONSENSUS

Our results from the previous section showed that the agreement rates for ring gestures and our specific set of referents are among the lowest ones ever reported in the literature. Possible explanations for this outcome are (1) the large number of degrees of freedom afforded by unconstrained finger and hand gestures, (2) our rigid criteria for clustering participants' gestures proposals into categories of similar types, and (3) the novelty of smart ring devices. Regarding the novelty aspect, ring-based gesture input represents a very recent interaction paradigm to which users will need time to accommodate before feeling confident about their preferences. In this section, we want to understand our results on agreement better by looking into how the elicitation process works. Specifically, we identified the following factors that we believe affect the magnitudes of agreement rates reported by *any* elicitation study:

> 1. *A priori* factors that relate to participants' individual traits and characteristics,

such as fine motor abilities to perform gestures, cognitive abilities to produce (sometimes abstract) associations between various categories and concepts, or previous experience with gesture input, i.e., the "legacy bias" [33]. In this section, we focus on discussing participants' creativity and motor skills.

> 2. Factors occurring *during* the study,

such as participants' commitment and dedication to the study. Elicitation studies, just like any participatory design studies, require great willingness from participants to commit to the task, disclose their views of the situation at hand, share their experience [5], and conform to the experimental setup, such as the think-aloud protocol [63]. We report in this section on the relationship between participants' thinking time to propose ring gestures and the resulted agreement rates.

> 3. *A posteriori* factors, occurring after the experiment

can influence the magnitude of agreement rates, such as the experimenter's choice of criteria to group participants' gestures into categories of similar types, which can be rigid (such as the criteria employed in this work; see the "Results" section) or relaxed (as we are about to discuss next in this section).

To our surprise, none of the above factors (except for the legacy bias [16,33,44] and thinking times [59,65]) have been considered before for gesture elicitation studies, despite the popularity of this methodology and its frequent application [26,32,38,43,44,45,50,57,58,59] over more than ten years since it was introduced [62,63]. In this context, our discussion from this section, besides unveiling interesting aspects regarding our participants' gesture input behavior with smart rings, represents a contribution to *any* gesture elicitation study and should be viewed as such.

Thinking Time, Fine Motor Skills, and Creativity Scores

RM ANOVA revealed a significant effect of NUMBER-OF-RINGS on participants' THINKING-TIME ($F_{(1,23)} = 13.697$, $p < .001$, $\eta_p^2 = .373$): our participants spent 48% more time thinking about gestures in the 1-ring condition ($M = 4.60$ s, $SD = 1.47$ s) than when using two rings ($M = 3.10$ s, $SD = 1.00$ s). We did not find any significant effect of REFERENT ($p = .075$, *n.s.*), nor an interaction between NUMBER-OF-RINGS and REFERENT ($p = .894$, *n.s.*) on THINKING-TIME.

Figure 5 shows the relationship between thinking times and agreement rates per REFERENT and NUMBER-OF-RINGS. Agreement rates decreased for longer thinking times for both the 1-ring (Pearson's $r_{(N=14)} = -.778$, $R^2 = .605$, $p < .001$) and 2-rings conditions ($r_{(N=14)} = -.336$, $p = .241$, *n.s.*), although only the former correlation was significant.

The more time participants took to think about gestures, the less agreement resulted. This finding can be interpreted in several ways. First, the more time participants allocated to the task, the more creative they presumably wanted to be and, consequently, they thought of gestures less likely to be proposed by others. Second, it is reasonable to assume that participants' first choice of a gesture (i.e., the gesture proposal coming to mind after a minimum thinking time) was likely to be found by other participants as well, probably due to some internal mechanism of understanding referents, e.g., flick to

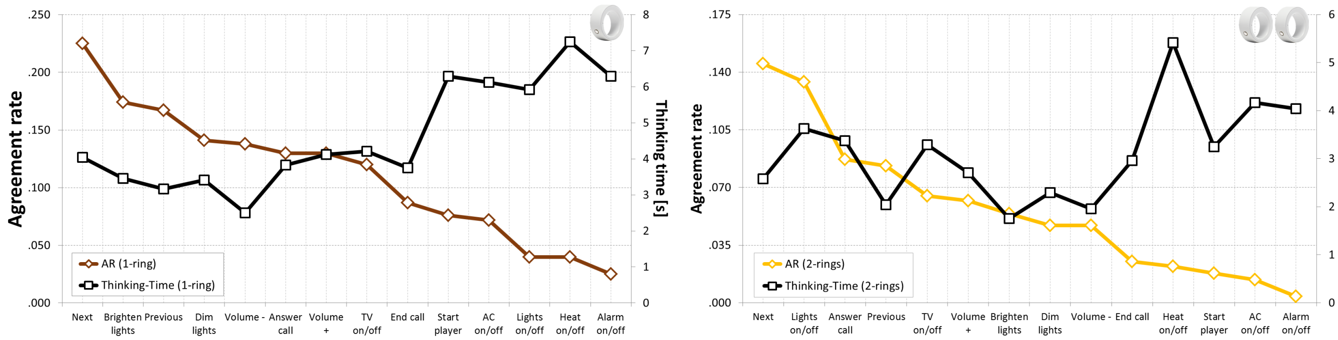

Figure 5. Relationship between AGREEMENT-RATE and THINKING-TIME for gestures performed using one ring (left) and two rings (right).

the left to advance to the next item in a list. It may also be that participants failed to produce highly similar gestures because some tasks exceeded their sensorimotor knowledge [6]. If that was the case, participants might have recurred to other types of knowledge to provide suitable gesture proposals, such as motor-intuitiveness, e.g., some gestures were proposed because of their convenient spatial or biomechanical properties. All these interpretations are interesting as a direct consequence of participants' individual traits, such as their cognitive and motor abilities to invent and articulate ring gestures.

Our participants' creativity scores varied between 46.4 and 81.6 ($M = 59.4$, $SD = 9.4$) on a scale from 0 to 100 (higher is more creative). Their fine motor skill levels varied between 7.3 and 14.1 ($M = 9.9$, $SD = 1.7$, lower is better). We found no difference in creativity between male and female participants ($t_{(22)} = -1.296$, $p > .05$, *n.s.*), but we did find that male participants performed 23% better at the motor skill test (9.0 versus 11.1, $t_{(22)}$=3.559, p=.002, r=.604). Informed by these results and our insights presented above, we computed correlations between CREATIVITY and THINKING-TIME for all participants and between MOTOR-SKILL and THINKING-TIME separately for male and female participants due to the difference in motor skill levels found between the two groups. We found a negative relationship between CREATIVITY and THINKING-TIME for both the 1-ring (Pearson's $r_{(N=24)} = -.143$) and 2-rings conditions ($r_{(N=24)} = -.150$), showing that higher creativity related to shorter thinking times to propose gestures. However, statistical significance was not achieved ($p > .05$), which prevent us to extrapolate these findings to the wider user population. We did find, however, a strong negative correlation between MOTOR-SKILL and THINKING-TIME for female participants ($r_{(N=10)} = -.748$, $R^2 = .560$, $p = .013$): higher fine motor skills in women were connected to shorter thinking times.

These results suggest that thinking time may be an important factor to the success of a gesture elicitation study: the way participants dedicate to the task may affect both consensus and the set of gestures. While we point to these aspects in the specific context of our ring gestures investigation, we believe that such interesting connections should be explored thoroughly by future work, as they apply to any gesture elicitation study.

The Gesture Pairing Criteria

The first step of the analysis process for elicitation studies consists in identifying gestures that look similar in order to compute agreement rates [62]. However, this process is inherently dependent on the designer's goals for the specific application for which gestures were elicited in the first place. Gesture pairing can be *rigid* or *relaxed* and, thus, may have an influence on the magnitudes of agreement rates.

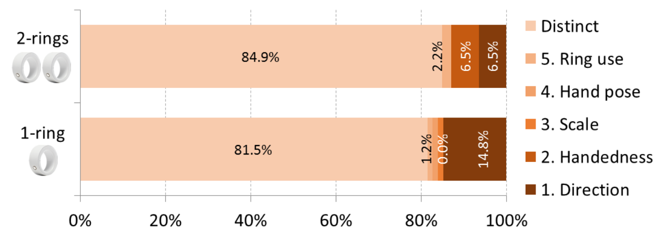

Figure 6. Percentage of gestures that become similar when relaxing grouping criteria. For example, 14.8% of all 1-ring gestures will merge into the same category if gesture *direction* is no longer important.

In this work, we adopted a set of five criteria to pair gestures into categories of similar types: *handedness*, *direction*, *scale*, *hand pose*, and *ring use*; see the "Experiment" section. It could be that our criteria were too rigid compared to other studies [43, 50,59,63], which would help explain our low agreement rates. Therefore, we wanted to see what happened when these criteria were relaxed. Figure 6 shows the percentage of gestures that merged after eliminating each of our criteria in a row. For example, by not considering gesture *direction* as important, 14.8% of the gestures in the 1-ring condition and 6.5% of the gestures in the 2-rings condition merged into the same category. In the end, the average agreement rates increased from .112 (1-ring) and .058 (2-rings) to .144 (maximum .442) and .074 (maximum .210), respectively, representing an increase of 28% on average. We can conclude that the criteria to group gestures has an influence on the magnitude of agreement rates.

Influence of the Methodology and Experiment Design

Besides the aforementioned factors, the methodology and experiment design can affect the level of agreement. For instance, we randomized the order of referents in our experiment to avoid bias and potential transfer effects from one referent to the next. However, with such an approach, it may be difficult for participants to identify relationships between referents and propose relevant gestures in consequence, e.g., brighten and dim lights are symmetrical referents, but this relationship is not explicitly presented to participants, who may or may not identify it. Presenting all the referents at once, or adopting a hybrid approach where groups instead of individual referents are randomly presented to participants may lead to different levels of agreement. Other aspects regard the possibility to propose more than one gesture for a referent (many-to-one relationship) or reusing the same gesture for more than one referent (one-to-many). In both cases, higher agreement is likely to be reached. Ultimately, such choices depend on the practitioner's goal, but we point to these aspects as we believe that they should be thoroughly examined by future work.

DESIGN GUIDELINES FOR SMART RING GESTURES

We discuss in this section some of our participants' gestures in more depth as we derive recommendations for ring gestures. However, the following should not be viewed as an absolute set of design guidelines, because of the too novel technology involved and, thus, limited time for users to become aware of their preferences, but rather as a set of proposals to inform further investigations and developments.

> ✍ Motion seems to be preferred over static gestures.

We found that static gestures (i.e., hand poses) were performed for 8.3% of all 1-ring gestures and 6.8% for 2-rings. Examples include emblems and cultural signs, such as the "thumbs up" gesture (Fig. 7f) or the "call me" sign. Motion gestures were proposed in 64.9% and 73.0% of all cases; see directional swipes (Fig. 7a,b), synchronized bimanual swipes (Fig. 7y), hands approaching or separating in space (Fig. 7n,o,p), fingers spreading (Fig. 7d,e), or relative movements of the hands, such as sliding, rubbing, or twisting (Fig. 7m,v,x).

> ✍ Users prefer "simple" gestures of the dominant hand.

Of all proposed gestures, 74.4% (1-ring) and 81.0% (2-rings) were "simple" according to our taxonomy, i.e., not reducible to simpler actions without losing meaning. Participants went for simplicity even when two rings were available: 37.2% of the 2-rings gestures involved just one hand, and only 6.8% used the nondominant hand. Also, we found that compound 2-rings gestures were less frequent than 1-ring gestures (19.0% *vs.* 25.6%), showing again a quest for simple gestures.

> ✍ Consider gesture designs that exploit the surface of the ring and/or its unique shape and form factor.

The smart rings literature has proposed some creative ring interactions, such as twisting and sliding the ring on the finger [4] or simultaneously touching parts of the ring's surface [27]. Our participants proposed gestures that not only rediscovered such expert designs, but went further. We found that participants used the ring surface in 8.9% of their 1-ring gestures and in 16.4% for 2-rings. Such gestures included taps on one ring, taps on both rings, and tapping rhythms (Fig. 7r,s), sliding the thumb along the ring's surface (Fig. 7h), closing the ring inside the fist (Fig. 7g,u), rotating the ring (Fig. 7t), pulling the ring out and putting it back on the finger, sliding the ring along the finger, or putting the two rings in contact (Fig. 7z).

> ✍ Reuse touch gestures and touch-based interaction paradigms from smartphones due to their familiarity.

We found that 30.1% of the gestures proposed in the 1-ring condition and 27.3% of the 2-rings gestures were variants of taps (performed on the ring) and directional swipes (in mid-air or on the ring's surface). The literature has documented this effect as the "legacy bias" [33]. Wobbrock et al. [63] made the observation *"It's a Windows World"* (p. 1089) in their study from 2009 when their participants often thought of the desktop paradigm when elicited for multi-touch gestures. In the nearly ten years that passed, we have witnessed large adoption of touchscreen devices.[6] We can now paraphrase Wobbrock et al. [63] and note *"It's a touch input world."* Thus, users' experience with touch gesture input should be exploited.

> ✍ Consider multiple gestures for the same command (many-to-one association), but also the same gesture for many commands (one-to-many), if permitted by context.

Prior work showed benefits of assigning more than one gesture to the same command [39] and that users perform the same gesture in many ways [2,40], at least for multi-touch input. On average, a referent received 13.3 distinct gestures (*SD*=3.1) in the 1-ring condition and 17.0 gestures (*SD*=2.9) in the 2-rings condition. It is also interesting to look at this aspect from the opposite perspective of "conflicts," i.e., the same gesture proposed for different referents by different participants. The average number of conflicts was 2.3 (*SD*=1.9) for the 1-ring condition and 1.7 (*SD*=1.1) for 2-rings. Many-to-one associations can enhance intuitiveness and "guessability" [62], while one-to-many mappings can minimize the effort to learn many gestures, provided that the context of execution is unambiguous, e.g., the gestures to turn on the TV and the AC unit can be the same, if the command to execute can be inferred from the context, e.g., the device the user is facing to.

> ✍ Favor symmetry in designing bimanual gestures.

We found that 42% of the gestures performed with two rings were symmetric, e.g., simultaneous taps on the two rings (Fig. 7s), approaching or spreading hands (Fig.s 7n,o,p), clapping, rubbing, or rotating hands (Fig. 7q,v,x).

> ✍ Gestures for operating imaginary objects in mid-air.

Some participants used gestures to manipulate imaginary objects, e.g., pushing a virtual button in mid-air (Fig. 7j) with variations (one push, two pushes, using the dominant or the nondominant hand, or both hands simultaneously), holding an imaginary remote control and pressing a button on it (Fig. 1i), or twisting a knob in mid-air (Fig. 1k). We recommend exploring such gestures to create intuitive mappings between movement and action, e.g., rotating a knob replicates a physical action with precise and unequivocal meaning.

> ✍ Design that fosters synergy with body gestures.

Some ring gestures were performed in relation to various body parts, such as placing the wearing hand close to the ear, raising the hand to the ear and touching the ring, placing both rings near the mouth (Fig. 7w), or gently blowing on the ring (Fig. 7l). We recommend investigation of such *body-referenced gestures*, which might benefit from high recall rates due to the mechanism of proprioception [29]. Body-referenced gestures could make the transition towards whole-body interaction, where rings are combined with other sensors [32,44,50].

[6] In fact, 8.4 billion smartphone units were shipped between 2009 and the time of this writing [47].

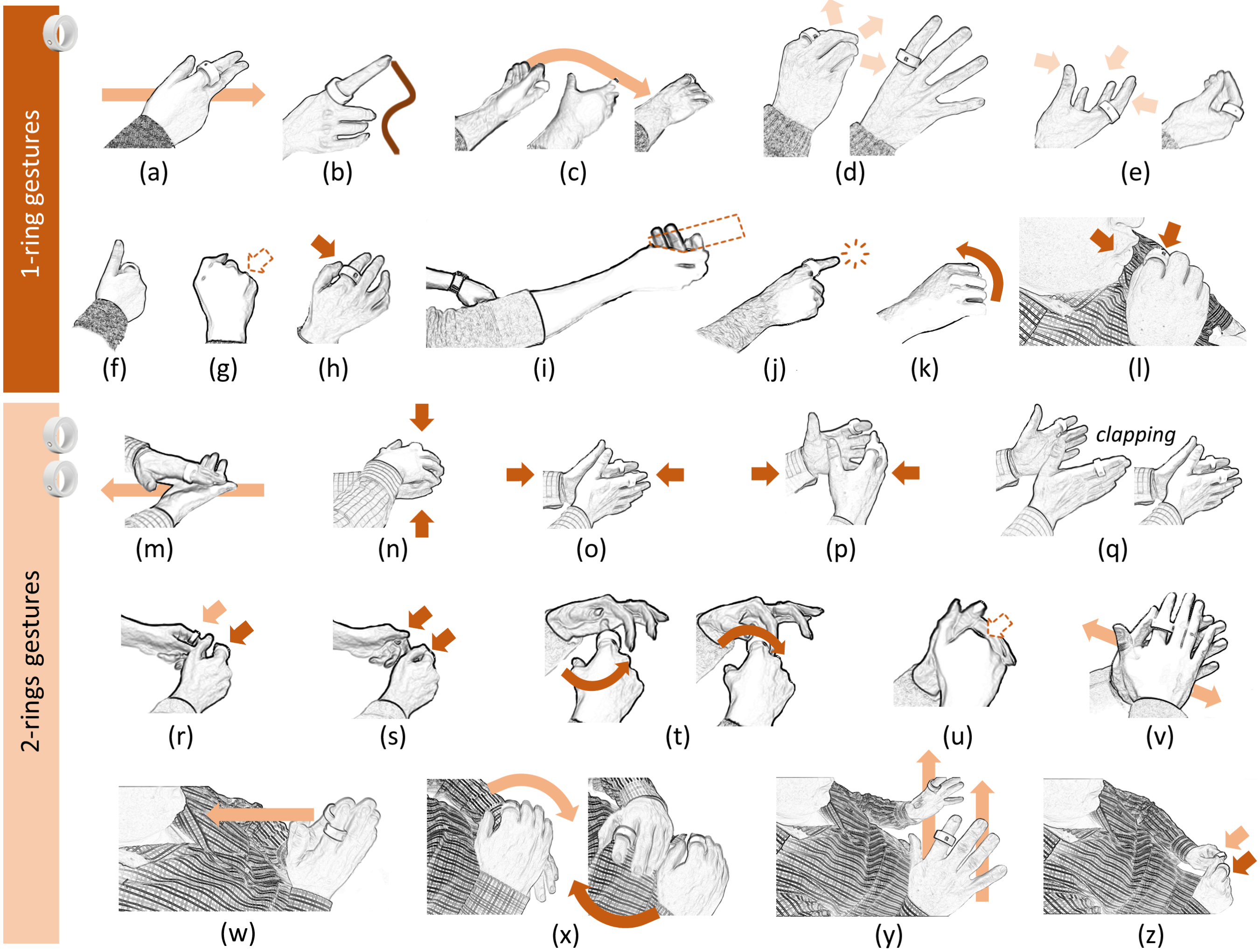

Figure 7. A selection of our participants' 1-ring (top) and 2-rings gesture proposals (bottom) illustrating various categories of mental models and articulation behavior for gesture input and smart rings. Gestures are referenced and discussed in the text.

> ✍ Design ring gestures that foster multimodal input.

One participant used voice commands in conjunction with ring gestures, e.g., raise the hand wearing the ring and say "player" out loud, while another participant placed the ring next to the mouth and blew on it. These examples suggest that multimodal input should be explored to make ring commands more intuitive and effective for various contexts of use.

CONCLUSION AND FUTURE WORK

We presented results from the first study conducted to understand users' preferences for ring gestures. We contributed a taxonomy to analyze ring gestures, a collection of gesture types, and a set of guidelines to inform further developments. Our gesture dataset can be freely downloaded and used for research purposes from http://www.eed.usv.ro/~vatavu.

Future work will look at the articulation details of bimanual gestures, i.e., the way the dominant and nondominant hands move to perform a ring gesture, such as by employing temporal algebra [1]. A detailed examination of participants' creativity is also envisioned by employing other, less generic tests, that look at specific aspects of creativity [10]. Allowing participants to suggest more than one gesture per referent is likely to lead to more consensus for novel technology, something to explore in the future as well. Also, connecting ring tap gestures with other gesture types, e.g., whole-body gestures, such as to deal effectively with the segmentation problem [54], is another interesting exploration. Our results on users' gesture input behavior can also be used to inform new smart ring technology, such as new sensors to embed into smart rings to detect various user actions, such as sliding, rubbing, twisting, or voice input. We leave such explorations for future work.

We believe that our investigation of user-defined ring gestures will be useful to practitioners that wish to prototype gesture interfaces for smart rings. At the same time, the factors that we outlined as important for reaching consensus in elicitation studies should be examined further by the community.

ACKNOWLEDGMENTS

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